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ESA Contract No. 4000109866/13/NL/MH

Abstract (issue 2)

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CONTENTS

1. INTRODUCTION

1.1 Scope

This document outlines the background, objectives and the main results of the project “Millimeter wave VAlidation STandard (mm-VAST) antenna” completed by the Technical University of Denmark (DTU) in collaboration with Danish company TICRA for the European Space Agency (ESA) under ESA contract no. 4000109866/13/NL/MH.

1.2 Applicable documents

[AD1] ESA Contract No. 4000109866/13/NL/MH, Appendix 2: Statement of Work.

1.3 Reference documents

[RD1] S. Pivnenko *et al.*, “Comparison of antenna measurement facilities with the DTU-ESA 12 GHz validation standard antenna within the EU antenna centre of excellence,” *IEEE Trans. Antennas Propagat.*, vol. 57, no. 7, pp. 1863– 1878, 2009.

1.4 Abbreviations

AD	Applicable Document
CFRP	Carbon Fiber Reinforced Plastic (Polymer)
CNC	Computer Numerical Control
CP	Circular Polarization
CTE	Coefficient of Thermal Expansion
DTU	Technical University of Denmark
EMS	Electromagnetic Systems
ESA	European Space Agency
LP	Linear Polarization
MCS	Mechanical Coordinate System
OCS	Optical Coordinate System
RD	Reference Document
RF	Radio Frequency
SoW	Statement of Work
VAST	Validation Standard

1.5 Background

Inter-comparisons of antenna test ranges serve the purpose of validating the measurement accuracy of a given range before it can be qualified to perform certain measurements, which is particularly important for space applications, where antenna specifications are very stringent. Moreover, by verifying the measurement procedures and identifying sources of errors and uncertainties, inter-comparison campaigns improve our understanding of strengths and limitations of different measurement techniques, which, in turn, leads to further improved measurement accuracies.

The lesson learned from early comparison campaigns executed by the Technical

University of Denmark (DTU) in the mid-1980s on some readily available antennas is that the proper inter-comparisons can only be done on dedicated antennas, whose design is driven by stringent requirements on their rigidity and mechanical stability. Furthermore, well-defined reference coordinate systems are essential. These principles have convincingly been proven valid by the VAST-12 antenna designed by DTU in the late 1980s, which in more than 20 years has demonstrated its usefulness and long-term value [RD1].

Currently, the satellite communication industry is actively commercializing the mm-wave frequency bands (K/Ka-bands) in its strive for wide frequency bandwidth and higher bit-rates. The next step is the exploration and exploitation of the Q/Vband. In this scenario, the European Space Agency (ESA) is expanding its portfolio of VAlidation STandard antennas (VAST) into mm-waves to ensure accurate measurements of the next generation communication antennas. This time, ESA demands all four bands (K/Ka/Q/V-bands) to be covered by a single VAST antenna. In response to this demand the Technical University of Denmark represented by two departments – Department of Electrical Engineering and Department of Wind Energy – in collaboration with TICRA has developed a new precision tool for antenna test range qualification and inter-comparisons at mm-waves – the DTU-ESA mm-VAST antenna.

1.6 Purpose and Tasks

The primary purpose of this project was to make available a well-characterized and mechanically and thermally stable multi-frequency reflector VAlidation STandard antenna for range qualification at mm-wave frequencies (mm-VAST).

The project involved four major tasks:

1) critical review and formalization of general requirements outlines in the Statement of Work (SoW) [AD1];
2) electrical design of the antenna,
3) mechanical design and manufacturing,
4) antenna testing.

2. REQUIREMENTS

To be able to serve as a measurement standard the mm-VAST antenna must be stable under various operational conditions, that is, under any orientation in gravity and within the temperature range of 20±5°C. Along with the required multi-band capability, this constituted the major challenge of the project. More specifically, any deformities of the mm-VAST antenna during tests, under rotations and temperature variations, should introduce an error less than 1/10 of the measurement accuracy being sought. With the typical measurement accuracy for the peak directivity at the DTU-ESA Spherical Near-Field Antenna Test Facility of 0.03 dB (1σ), the stability requirement translates into the measurement uncertainty, which can be introduced by mm-VAST, of 0.003 dB (1σ). In combination with a short wavelength (6 mm) at the highest operational frequency, this requirement results in maximum acceptable deformations of the antenna structure of the order of microns.

Main electrical requirements are summarized in Table I. It should be noted that the mm-VAST antenna is not required to cover all frequencies in each of the four bands. One frequency per band is enough; the selected ones are shown in parentheses.

Besides that, the antenna shall have well-defined mechanical and optical coordinate systems (MCS and OCS, respectively).

Table I. Requirements to the mm-VAST antenna

Operational frequencies	Frequency 1 within 17.5–20.2 GHz (19.8 GHz) Frequency 2 within 27.5–31.0 GHz (30 GHz) Frequency 3 within 37.5–40.5 GHz (38 GHz) Frequency 4 within 47.2–50.2 GHz (48 GHz)
Gain	Frequency 1 and 2: 30–35 dBi Frequency 3 and 4: 33–38 dBi
Polarization	Reconfigurable between linear and circular at all operational frequencies
Co-polar pattern	Challenging to measure: • near-sidelobes (1st-3rd) in the range 18–25 dB below peak • deep nulls • far-out sidelobes ($\theta > 20°$) at least 30 dB below peak • an asymmetry • different beamwidths in the orthogonal planes • flat-top or split main beam
Cross-polar pattern	• > 20 dB below the co-polar peak in the main beam region • null in the main beam region
Return loss	10–20 dB

3. ELECTRICAL DESIGN

The mm-VAST is a single offset reflector antenna (Figure 1), whose design was done by the Danish company TICRA. Having made an extensive parametric investigation, TICRA identified antenna parameters optimal with respect to the requirements. The reflector surface is chosen to be an astigmatic parabola with different focal lengths in the orthogonal planes, which produces the desired elliptical beam as well as reduces the variation of the directivity over the large frequency span from Frequency 1 to Frequency 4. More specifically, the reflector is defined by the following equation

$$z = \frac{x^2}{4F_x} + \frac{y^2}{4F_y}$$

where F_x mm and F_y mm are focal lengths in the xz- and yz-planes, respectively. The square aperture facilitates the near-sidelobes in the specified range (18–25 dB below peak) and moderate spill-over loss. The main geometrical parameters of the antenna are provided in Table II.

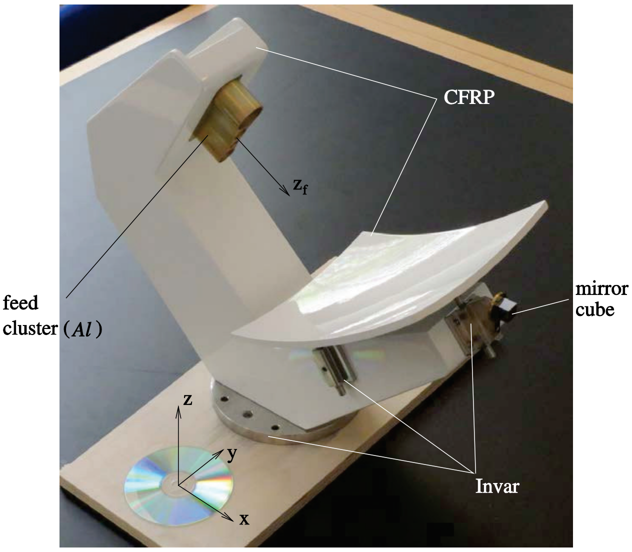

Figure 1. mm-VAST antenna, weight 9.5 kg.

Table II. Geometrical parameters of the mm-VAST antenna

Aperture	230 × 230 mm
Focal lengths	F_x = 167 mm F_y = 220 mm
Offset	200 mm
Offset angle	57.6°

The antenna is fed by a feed cluster of four Pickett-Potter horns, one for each frequency. This kind of horns was chosen for its extremely low cross-polarization. The horn axes are aligned in the antenna symmetry plane to ensure a deep null of the linear cross-polarization, while the apertures are kept in one plane to ease the manufacturing. The sizes of the input circular waveguides of the feed horns were selected so that only the fundamental TE_{11} mode can propagate. This was done to improve reproducibility of the results, when the antenna is manually reconfigured between the operational frequencies and the polarization modes. The reconfiguration is done by mounting to the relevant horn a dedicated component – either a transition for linear polarization (LP) or an LP-to-CP polarizer for circular polarization (CP). Other horns are terminated with well-defined loads – short-circuits in our case. The feed cluster and all waveguide components were designed and manufactured at the Electromagnetic Systems (EMS) group of the Department of Electrical Engineering (DTU).

4. MECHANICAL DESIGN AND MANUFACTURING

The structural design of the antenna was done by the Department of Wind Energy at DTU, taking outset in the department's unique experience in composite materials and structures. The design involves such materials as carbon fiber reinforced plastic (CFRP) for the antenna frame and the reflector, and Invar for the reflector mounting brackets and the flange (see Figure 1). Invar was chosen for its coefficient of thermal expansion (CTE) nearly matching that of CFRP. The material for the feed cluster was selected to be aluminum.

Operational wavelengths at millimeter waves imposed strict requirements not only to the stability of the mm-VAST antenna, but also to the fabrication and alignment tolerances. To meet these tight tolerances all metal parts of the antenna as well as the moulds for the frame and the reflector were made on computer numerical control (CNC) machines. A unique antenna assembly and alignment procedure was developed to ensure that all key components of the antenna – the reflector, the feed, the frame, the mounting flange, and the mirror cube – were perfectly aligned with respect to each. The reflector surface was coated with silver paint and finished with white protective paint.

The mechanical coordinate system of the mm-VAST antenna is defined by the normal to the mounting flange with orientation defined by a permanently attached precision level. The optical coordinate system is defined by a mirror cube placed behind the reflector.

Since the mm-VAST antenna is meant to be sent around to different measurement facilities, a dedicated flight case with an integrated toolbox for the waveguide components has been designed and procured.

5. TESTING

The manufactured mm-VAST antenna passed a series of tests to check its mechanical and thermal stability, its environmental survivability, and to provide a set of accurate reference results for all configurations at all frequencies.

The RF measurements revealed a good performance of the fabricated antenna. In all bands, the values of the measured reflection coefficient around the nominal frequencies satisfy the requirements.

The stability was verified by checking the orientation of the OCS in MCS as well as the LP patterns at Frequency 1 (Figure 2) before and after the survivability environmental test. It was concluded that the observed differences were much smaller than the measurement uncertainties and thus the electrical stability of the mm-VAST antenna is very high, beyond the detection level.

The final operational frequencies for the mm-VAST antenna were slightly adjusted to correspond to the minimum CP axial ratio found in each band (see Table III). These frequencies are the same for LP and CP in each band.

Thorough analysis of the results of the electrical tests has shown that the mm-VAST antenna is fully compliant to the majority of the requirements with only minor nonconformances on a few parameters, which were deemed acceptable.

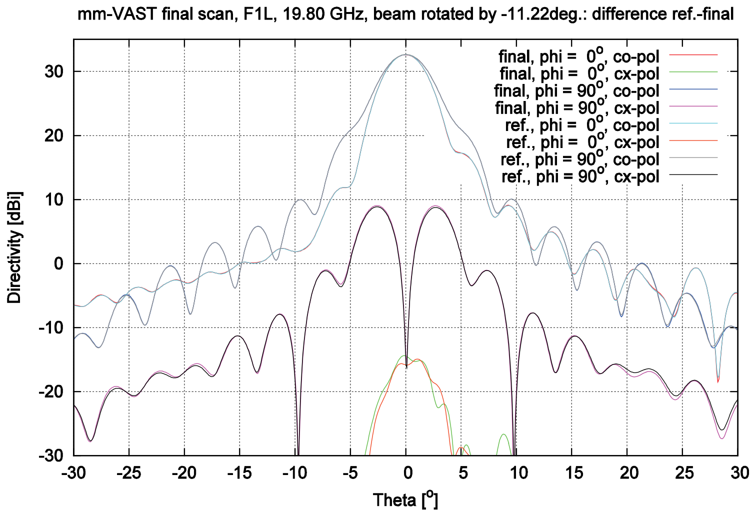

Figure 2. LP radiation pattern cuts at Frequency 1: comparison of the results before (reference) and after (final) the environmental tests.

Table III. Final operational frequencies of the mm-VAST antenna

Frequency 1	19.76 GHz
Frequency 2	30.04 GHz
Frequency 3	37.80 GHz
Frequency 4	48.16 GHz

6. CONCLUSIONS

A new antenna test range verification tool at millimeter waves – the mm-wave VAlidation STandard antenna (mm-VAST) – has been designed, manufactured and tested at the Technical University of Denmark (DTU) in collaboration with Danish company TICRA under an ESA project. The mm-VAST is a multiband offset reflector antenna fabricated of composite materials for extreme mechanical and thermal stability. The antenna operates at 20/30/40/50 GHz bands and is LP/CP reconfigurable. The antenna will facilitate inter-comparison and validation of antenna measurement ranges at mm-waves addressing the on-going deployment of satellite communication services at 20/30 GHz (K/Ka-band) as well as future commercial use of the 40/50 GHz bands (Q/V-band).

The single offset reflector antenna scheme has proven to be a configuration of choice for VAST antennas. Its structural simplicity eases the assembly and alignment, while still providing enough flexibility for shaping the radiation pattern to achieve desirable features. Both VAST-12 [RD1] and mm-VAST utilize this configuration and it can be recommended for future VAST antennas at higher frequencies.

The project has been completed and all goals were successfully accomplished.

7. PUBLISHED PAPERS

1. S. Pivnenko, O. S. Kim, O. Breinbjerg, K. Branner, C. Markussen, R. Jørgensen, N. V. Larsen, and M. Paquay, "DTU-ESA millimeter-wave validation standard antenna – requirements and design," in Proc. 36th Symp. Ant. Meas. Tech. Assoc. (AMTA), Tucson, Arizona, USA, 12-17 October 2014.

2. O. S. Kim, S. Pivnenko, O. Breinbjerg, R. Jørgensen, N. V. Larsen, K. Branner, P. Berring, C. Markussen, and M. Paquay, "DTU-ESA millimeter-wave validation standard antenna – detailed design," in Proc. 9th European Conference on Antennas and Propagation (EuCAP'2015), Lisbon, Portugal, 12-17 April 2015. (Best Measurement Paper Award).

3. K. Branner, P. Berring, C. Markussen, O. S. Kim, R. Jørgensen, S. Pivnenko, and O. Breinbjerg, "Structural design of the DTU-ESA millimeter wave validation standard antenna," in Proc. 20th International Conference on Composite Materials (ICCM20), Copenhagen, Denmark, 19-24 July 2015.

4. O. S. Kim, S. Pivnenko, O. Breinbjerg, R. Jørgensen, N. Vesterdal, K. Branner, P. Berring, C. Markussen, and M. Paquay, "DTU-ESA millimeter-wave validation standard antenna – manufacturing and testing," in Proc. 37th Antenna Meas. Techn. Assoc. (AMTA) Symp., Long Beach, CA, USA, 11-16 October, 2015.

5. S. Pivnenko, O. S. Kim, O. Breinbjerg, R. Jørgensen, N. Vesterdal, K. Branner, P. Berring, C. Markussen, and M. Paquay, "DTU-ESA millimeter-wave validation standard antenna – performance verification," in Proc. 36th ESA Antenna Workshop on Antennas and RF Systems for Space Science, ESTEC, Noordwijk, The Netherlands, 06-09 October 2015.